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The economic and environmental impact of power to hydrogen/power to methane facilities on hybrid power-natural gas energy systems

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Abstract. The curtailment of renewable energy would be reduced by converting it to hydrogen or methane using power to hydrogen (P2H) facilities or power to methane (P2M) facilities. Both hydrogen and methane can be injected into the existing natural gas system which has significant potential to unlock the inherent flexibility of integrated energy systems. The coordinated operation strategy of the hybrid power-natural gas energy systems considering P2H and P2M is proposed aiming to minimize the operational cost. In addition, a method to calculate the higher heating value of hydrogen-natural gas mixture is presented along with a strategy for handling the constraints of hydrogen mixture level limits. The simulation results of three case studies demonstrate the economic and environmental benefits of P2H/P2M in terms of reductions in cost, CO_2 emissions and wind power curtailment. The differences in benefits between P2H and P2M have also been compared and analyzed.

Key words: power to hydrogen (P2H); power to methane (P2M); hydrogen energy; hybrid power-natural gas energy systems; renewable energy

1 Introduction

In order to reduce pollutant emissions, CO_2 emissions and the consumption of fossil fuels, renewable energy such as wind and photovoltaics are increasing continuously. However, the intermittency of wind and solar energy impose a significant challenge for energy system reliability. How to increase renewable generation and reduce the curtailment is becoming one of the key issues for the power systems. The development of power to gas (P2G) technologies [1-9] and increasing interaction between power systems and natural gas systems creates new opportunities for managing the fluctuation of renewable energy and increasing its accommodation. Renewable generation such as wind power generation could be used to produce hydrogen and methane (i.e. synthetic natural gas) using the power to hydrogen process (P2H) and the power to methane process (P2M) [10-11], respectively. In the power to hydrogen process, hydrogen is generated by electrolysis, whereby water is decomposed into hydrogen and oxygen. In the power to methane process, methane is formed by electrolysis and methanation which requires hydrogen resulting from electrolysis along with carbon dioxide [11-13]. The chemical reactions can be found below.

$$2H_2O \xrightarrow{\text{electrolysis}} 2H_2 + O_2 \qquad \text{(process of electrolysis)}$$

$$4H_2 + CO_2 \xrightarrow{\text{hthp}} CH_4 + 2H_2O \qquad \text{(process of methanation)}$$

Recently, studies on application of P2H and P2M are paid great attention [3,14-19]. It is widely expected that hydrogen will play an increasingly important role as an energy carrier [15,20-21]. Hydrogen can be used in many sectors and in many ways e.g. industrial, domestic, transport and injection to the natural gas network within the allowed level of hydrogen content [3,17-18]. Methane can be directly injected into the natural gas network with no limits. Irrespective of it being hydrogen or methane injected into the natural gas network, it will have a significant impact on the operation of both the power system and the natural gas system. From the schematic of a hybrid power-natural gas energy system in Fig. 1, it can be seen that the natural gas energy system uses hydrogen or methane produced by P2H or P2M to guarantee the continuity of gas supply and the curtailed renewable generations can be stored and transported in the existing natural gas energy system. For the power system, as the curtailed wind power is used to produce hydrogen and methane by P2H and P2M, the accommodation of the renewable generation can be

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increased. Meanwhile, the power system requires more flexible power from the natural gas energy system to manage peak load using the gas-fired generator units [2,19]. P2H and P2M are loads on the power system but a source of gas for the natural gas system. Besides, the gas-fired generator units are the load of natural gas energy system and the generators of the power system. Thus, the operation of the hybrid power-natural gas energy systems is interactive and the operational cost, emissions and reliability of both systems will be affected by P2H and P2M. Therefore, how to achieve interactive operation and how to assess the economic and environmental impact of P2H and P2M are key issues for hybrid power-natural gas energy systems.

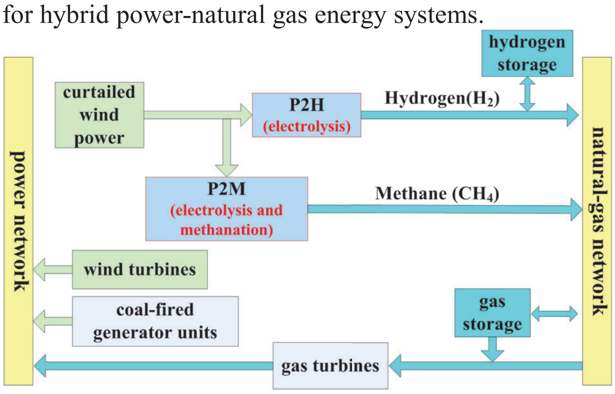

Fig. 1 - Diagram of hybrid power-natural gas energy systems.

Recently, research has been carried out on optimal operation of hybrid power-natural gas energy systems considering P2M [5-7,22-29]. Two-level optimal flow structure [5,13,23-24] is mostly used with different optimal objectives such as minimum total operational cost [5,22-24], maximum wind power accommodation [25] or minimum energy purchase cost [26]. Usually the mixed-integer linear programming method [2] and interior point method [27] are used to solve these optimal operation models. However, P2H is rarely considered in the above research. P2H without the methanation process has much higher efficiency than P2M, which might bring further cost reduction. Some effort has been made on how to integrate P2H with renewable energy [17, 29-36].

Gondal [17] gave an introduction to hydrogen integration via power and gas networks and the utilization of hydrogen as energy storage has also been illustrated [32-34]. The current research of the hybrid energy systems with P2H is mainly about unit commitment [31], the potential for P2H to cut down wind power curtailment [35] and the utilization of P2H to balance load [25]. Comparison of the economic and environmental benefits of P2H and P2M is rarely studied. Due to the differences in efficiency and injection limit, P2H and P2M have different economic and environmental impact on hybrid power-natural gas energy systems. Therefore, it is essential to conduct a study on the economic and environmental benefits comparison between P2H and P2M.

To address the above research gap, this paper employs an optimal coordinated operational model of the hybrid power-natural gas energy system with both P2H and P2M. Then the economic and environmental impact of P2M/P2H is analyzed and compared whereby several case studies carried out on a hybrid IEEE 39-bus power system and Belgian 20-node gas system. The simulation results illustrate the benefits of P2H and P2M in terms of reduction of operational cost, decline of CO_2 emissions, and more accommodation of wind power. Moreover, the differences between P2H and P2M in terms of the economic and environmental benefits are also compared considering their differences in efficiency and the injection limits.

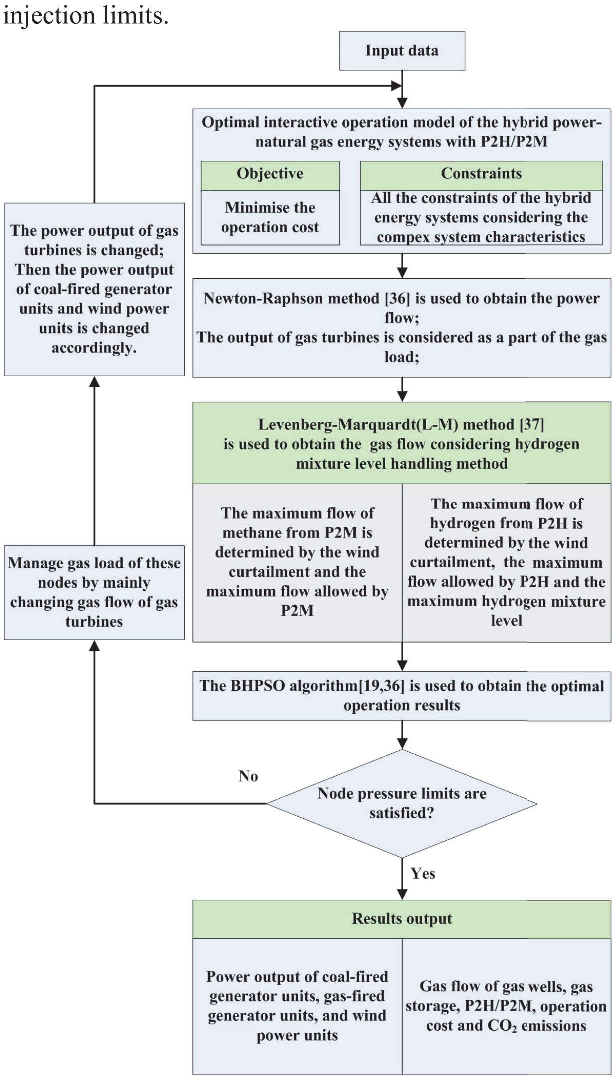

Fig. 2 - Flow chart of the optimal operation problem.

2 Problem formulation

To assess the economic and environmental impact of P2H and P2M on the hybrid power-natural gas energy system, an optimal operational model needs to be properly established. In this paper, a coordinated optimal strategy that minimizes the total operational cost is proposed. The flow chart of this non-convex, non-linear and multi-constraint optimization problem is shown in Fig. 2. The operation of the power and natural gas systems interact via P2H/P2M and gas turbines. For electricity grid, the power flow is calculated by the Newton-Raphson method [36] while in natural gas network the gas flow is obtained using the Levenberg-Marquardt (L-M) method [37]. To solve this non-convex, non-linear and multi-constraint optimization problem, the black-hole particle swarm optimization algorithm (BHPSO) [19,36] is adopted. When the constraints such as the node pressures of the natural-gas system are not satisfied, the inflow of gas turbines will be adjusted with consequent changes in power output of gas turbines. The details are described below.

2.1 Objective

The objective of this optimal problem is to obtain the minimum operational cost of the hybrid power-natural gas system. From Equation (1), it can be seen that the operational cost includes four parts. The first part (the quadratic equation) represents the operational cost of thermal generator units such as coal-fired and gas-fired units. In this study, the valve point effect [36] is not considered. The second part is the cost of gas from wells and gas storage. The operational cost of P2H/P2M facilities is taken into account as the third part. The last part is the gas cost saving due to the injection of hydrogen and methane into the natural gas network. This is summarized as:

$$\begin{aligned}\text{Min} \quad F_c = &\sum_{i=1}^{N_G}\sum_{t=1}^{T} a_i P_{Gi}^2(t) + b_i P_{Gi}(t) + c_i \\ &+ \sum_{n=1}^{N_w}\sum_{t=1}^{T} Q_{wn}(t) u_{wn}(t) + \sum_{m=1}^{N_{gs}}\sum_{t=1}^{T} Q_{gs,m}(t) u_{gs,m}(t) \\ &+ \sum_{k=1}^{N_{HM}}\sum_{t=1}^{T} P_{HM,k}(t) u_{HM,k} - \sum_{k=1}^{N_{HM}}\sum_{t=1}^{T} Q_{HM,k}(t) u_{ave}(t)\end{aligned} \tag{1}$$

where F_c is the operational cost of the hybrid power-natural gas energy systems; N_G is the number of power generators; T is the number of time periods; $P_{Gi}(t)$ is the power generation output at time t; a_i, b_i, c_i are coefficient of the generator fuel cost; N_w, $N_{gs,}$ N_{HM} represent the number of gas wells, gas storage and P2H/P2M units, respectively; $Q_{wn}(t)$ and $u_{wn}(t)$ are, respectively the gas flow and price of the nth gas well at time t; $Q_{gs,m}(t)$ and $u_{gs,m}(t)$ are the gas flow and storage price of gas storage m at time t; $u_{HM,k}$ is the operational cost of P2H/P2M k; $Q_{HM,k}(t)$ is the gas flow of P2H/P2M k at time t; $u_{ave}(t)$ is the average gas price; $P_{HM,\,t}(t)$ is the power supplied to the P2H/P2M facilities at time t.

In this paper, modelling the relationship between power and the corresponding gas flows at various parts of the hybrid system is very important. The interlinks includes the relationship between power supplied to the P2H/P2M facilities $P_{HM,\,k}(t)$ and the gas flow out $Q_{HM,k}(t)$; and the relationship of power output of gas turbines $P_{GT,i}(t)$ and the gas consumed $Q_{GT,i}(t)$. These relationships are described as shown below.

$$\begin{cases} P_{HM,k}(t) = Q_{HM,k}(t) \cdot HHV_{H_2} \cdot \eta_{HM,k} & \text{(for P2H)} \\ P_{HM,k}(t) = Q_{HM,k}(t) \cdot HHV_{NG} \cdot \eta_{HM,k} & \text{(for P2M)} \end{cases} \tag{2}$$

where HHV_{H2} and HHV_{NG} are the higher heating value of hydrogen and methane, respectively; $\eta_{HM,k}$ is the efficiency of the P2H or P2M process. In this paper, the higher heating value of hydrogen and methane is set as 12.75 MJ/m^3 and 39.5 MJ/m^3 , respectively.

In the same way, the relationship of $P_{GT,i}(t)$ and $Q_{GT,i}(t)$ is given as described below.

$$\begin{cases} P_{GT,i}(t) = Q_{GT,i}(t) \cdot HHV_{mix} \cdot \eta_{GT,i} & \text{(for P2H)} \\ P_{GT,i}(t) = Q_{GT,i}(t) \cdot HHV_{NG} \cdot \eta_{GT,i} & \text{(for P2M)} \end{cases} \tag{3}$$

where $\eta_{GT,i}$ is the energy conversion efficiency of the ith gas turbine; and HHV_{mix} is the higher heating value of the hydrogen-natural gas mixture which can be calculated as shown below.

$$HHV_{mix} = HHV_{H_2} \cdot r_{H_2} + HHV_{NG} \cdot (1 - r_{H_2}) \tag{4}$$

where r_{H2} is the hydrogen mixture level. As HHV_{NG} is much higher than HHV_{H2}, the more hydrogen injected into the natural gas network, the lower HHV_{mix} would be. For this reason, the hydrogen mixture level may be constrained below an allowed level. For different countries and regions, the allowed level is different [12].

2.2 Equality constraints

Due to the complicated characteristics of the power system and the natural gas system as well as the coupling characteristics of the hybrid power-natural gas energy systems, the constraints of this optimal problem are quite complex. The equality constraints that depict the network fundamentals are as described below.

(1) Power load balance equation

The power load and power generation of power system must be balanced at all times.

$$P_L(t) + \sum_{k=1}^{N_{HM}} P_{HM,k}(t) - \sum_{i=1}^{N_G} P_{Gi}(t) = 0 \tag{5}$$

where $P_L(t)$ is the power load at time t.

(2) Gas flow equation of pipelines

The natural-gas system satisfies the mass conservation law of fluid dynamics and Bernoulli equation in the operation. The gas flow of pipelines and gas pressure of gas nodes are interrelated which can be modeled as presented below [27].

$$\frac{Q_{ij}^{in}(t) + Q_{ij}^{out}(t)}{2}\left|\frac{Q_{ij}^{in}(t) + Q_{ij}^{out}(t)}{2}\right| = C_{ij}\left(H_i(t)^2 - H_j(t)^2\right) \tag{6}$$

where $Q_{ij}^{in}(t)$ and $Q_{ij}^{out}(t)$ are the injection and withdrawal gas flow of pipeline ij respectively (Pipeline ij is the pipeline between gas nodes i and j); $H_i(t)$ and $H_j(t)$ are gas pressure of gas nodes i and j, respectively; C_{ij} is a constant related to the gas compressibility factor as well as the length, diameter, temperature of pipeline ij.

(3) Line pack equation

The injection gas flow and the withdrawal gas flow of the same pipeline would be different because of the compressibility of natural gas. Some excess natural gas stored in the pipelines is called line pack. The line pack of pipeline ij can be modeled as shown below [38].

$$L_{ij}(t) = \omega_{ij}\frac{H_i(t) + H_j(t)}{2} = L_{ij}(t-1) + Q_{ij}^{in}(t) - Q_{ij}^{out}(t) \tag{7}$$

where $L_{ij}(t)$ is the line pack of pipeline ij at time t; ω_{ij} is a constant related to pipeline parameters, gas constant, compressibility factor, gas density and gas temperature.

(4) Gas flow balance equation for each node

For each gas node, the gas flows into the node and out of the node must be equal [19].

$$\sum_{n\in i} Q_w(t) + \sum_{m\in i} Q_{gs,m}(t) + \sum_{k\in i} Q_{HM,k}(t) - \sum_{j\in SI(i)} Q_{ij}^{in}(t) + \sum_{j\in SO(i)} Q_{ij}^{out}(t) - Q_{GT,i}(t) - Q_{Li}(t) = 0 \tag{8}$$

where $Q_{GT,i}(t)$ and $Q_{Li}(t)$ indicate the gas flow injected to gas-fired generator units and the gas load at gas node i at time t, respectively; $SI(i)$ is the set of pipeline ij which contains gas node i as the input node; and $SO(i)$ is the set of pipeline ij which has gas node i as the output node.

2.3 Inequality constraints

The operational limits of the integrated system are modelled as a series of inequality constraints which can be found below. From formulas (9) to (16), they present the limits of power output, ramp rate limits of power units, line capacity limits, gas flow limits of gas wells, gas flow limits and capacity limits of gas storage, gas flow limits of P2H/P2M.

$$P_{Gi}^{\min} \le P_{Gi}(t) \le P_{Gi}^{\max} \tag{9}$$

$$\begin{cases} P_{Gi}(t) \ge \max\left\{P_{Gi}^{\min}, P_{Gi}(t-1) - \Delta P_{Gi}^{down}\right\}, & P_{Gi}(t) \le P_{Gi}(t-1) \\ P_{Gi}(t) \le \min\left\{P_{Gi}^{\max}, P_{Gi}(t-1) + \Delta P_{Gi}^{up}\right\}, & P_{Gi}(t) \ge P_{Gi}(t-1) \end{cases} \tag{10}$$

$$S_l(t) \le S_l^{\max} \tag{11}$$

$$Q_{wn}^{\min} \le Q_{wn}(t) \le Q_{wn}^{\max} \tag{12}$$

$$Q_{gs,m}^{\min} \le Q_{gs,m}(t) \le Q_{gs,m}^{\max} \tag{13}$$

$$V_m^{\min} \le V_m(t) \le V_m^{\max} \tag{14}$$

$$H_i^{\min} \le H_i(t) \le H_i^{\max} \tag{15}$$

$$Q_{HM,k}^{\min} \le Q_{HM,k}(t) \le Q_{HM,k}^{\max} \tag{16}$$

where $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ represent the minimum power output and maximum power output of power unit i, respectively; $\Delta P_{Gi}^{up}(t)$ and $\Delta P_{Gi}^{down}(t)$ represent the ramp up rate and the ramp down rate of power unit i, respectively; $S_l^{\max}$ is the maximum line capacity of line l in the power system; $Q_{wn}^{\min}$ and $Q_{wn}^{\max}$ represent the minimum and maximum gas flow of gas well n; $Q_{gs,m}^{\min}$ and $Q_{gs,m}^{\max}$ represent the minimum and maximum gas flow of gas storage m; $V_m(t)$ is the volume of gas in storage m at time t and $V_m^{\min}$ and $V_m^{\max}$ are the minimum and maximum gas storage capacity, respectively; $H_i(t)$ is the pressure at gas node i at time t. $H_i^{\min}$ and $H_i^{\max}$ are the minimum and maximum gas pressure; $Q_{HM,k}^{\min}$ and $Q_{HM,k}^{\max}$ represent the minimum and maximum gas flow of P2H/P2M k.

All these inequality constraints are handled by the method proposed in [19,36]. For P2H unit, if the hydrogen mixture level of the kth P2H unit at time t ($Q_{k,P2H}(t)$) exceeds the maximum level $B_{k,max}$, the following handling method is proposed as shown below.

$$Q_{k,P2H}(t) = Q_{k,P2H}(t) - \left[\left(\sum_{k=1}^{N_{P2H}} Q_{k,P2H}(t) - \left(\sum_{n=1}^{N_w} Q_{wn}(t) + \sum_{m=1}^{N_{gs}} Q_{gs,m}(t) + \sum_{p=1}^{N_{pipeline}} L_p(t)\right) \cdot B_{k,\max}(t)\right) / \sum_{k=1}^{N_{P2H}} Q_{k,P2H}(t)\right] \cdot Q_{k,P2H}(t) \tag{17}$$

where N_{P2H} is the number of P2H; $N_{Pipeline}$ is the number of pipelines; $Q_{k.P2H}$ (t) is the gas flow of P2H k at time t; A 10% hydrogen mixture affects the calorific value of the gas below desired level [17], and in many regions, the mixture level is limited below 5% [13]. So the maximum hydrogen mixture level $B_{k,max}$ in this paper is set as 3%.

2.4 Compressor

The compressors are used to boost pressures of natural gas network, which can help the natural gas transporting to each gas load. In this paper, the compressors work by consuming the natural gas. The consumed gas flow of compressor z, $Q_{cz}^{consume}(t)$, is calculated as shown below [38].

$$Q_{cz}^{consume}(t) = \beta_{cz} \frac{Q_{cz}(t)}{\eta_{cz} \cdot \tau} \cdot \left(\left(\frac{M_{oz}(t)}{M_{iz}(t)} \right)^{\tau} - 1 \right) \tag{18}$$

where β_{cz} is the energy conversion coefficient of compressor z; $Q_{cz}(t)$ is the gas flow flowing through compressor z at time t; η_{cz} is the efficiency of compressor z; $\tau=(\alpha-1)/\alpha$ and α is variability index of compressors; $M_{oz}(t)$ and $M_{iz}(t)$ are the pressure of output node and input node of compressor z, respectively.

3. Case studies

3.1 System description

The hybrid power-natural gas energy systems composed of the revised IEEE 39-bus power system and Belgian 20-node gas system [19] is used in the case studies. The parameters of the hybrid power-natural gas system are from [19]. The efficiency of the P2H and P2M processes are taken as 73% and 64%, respectively. It is assumed that the theoretical predicted wind power output is given over a 24 hour period; a day with a large peak-valley difference is shown in Fig. 3. The CO_2 emissions of coal and gas-fired generator units are set as 0.89kg/kWh and 0.39 kg/kWh, respectively [19]. The optimal operation of this hybrid power-natural gas energy systems is simulated using Matlab to assess the economic and environmental impact of P2H/P2M on the hybrid power-natural gas energy systems in the following three case studies.

Case 1: No P2H and P2M facilities are considered.
Case 2: Only P2H facilities are considered with the maximum hydrogen mixture level 3% vol.
Case 3: Only P2M facilities are considered.

The operational results are summarised in Table 1. The power output comparison of wind power units, coal-fired generator units and gas-fired generator units is shown in Fig. 3 and Fig. 4. The gas flow of each gas well, gas flow of each gas storage, gas flow of P2H and gas flow of P2M are given in Tables 2-4. It is should be noted that the gas flow of gas storage is shown negative when gas is flowing out of the gas storage. The comparison among case studies in terms of absorbed wind power and volume of gas storage can be found in Fig. 5 and Fig. 6.

	Case 1	Case 2	Case 3
Operational cost /M$	2.379	2.364	2.374
CO_2 emissions/ tonnes	72180	71260	71430
Rate of wind power curtailment	14.87%	5.05%	1.60%
Wind power absorbed by P2H/P2M/MWh	0	1623.5	2194.1

Table 1 - Operation results of the hybrid power-natural gas energy systems.

3.2 Results analysis

From the simulation results, the economic benefits and environmental benefits of P2H/P2M can be seen from the following aspects.

(1) In Table 1, the operational cost is reduced by $ 15000 with P2H and $ 5000 with P2M, respectively. It is mainly because that considerably more wind power is accommodated when P2H/P2M is considered, and hence the operational cost of coal-fired generator units and gas-fired generator units is cut down. Additionally, in case 2 and case 3, gas produced by P2H/P2M is injected into gas network and gas flow of gas wells including the injected gas from P2H/P2M is much higher which can be found from Table 2.

(2) The CO_2 emissions are reduced by 920 tonnes with P2H and 750 tonnes with P2M, respectively. That's also due to increased wind power accommodation with P2H/P2M. The emissions from coal-fired generator units and gas-fired generator units are declined a lot.

(3) From Table 1 and Fig. 3, it is obvious that the rate of curtailed wind power is declined from 14.87% to 5.05% (with P2H) and to 1.60% (with P2M), respectively. If the cost of the curtailed wind power is set as 100$/MWh, the curtailment cost is saved by $ 1.6×10^5 with P2H and $ 2.2×10^5 with P2M, respectively.

(4) From Table 1 and Fig. 5, as we can see that the wind power absorbed by P2H and P2M is 1623.5 MWh and 2194.1 MWh, respectively.

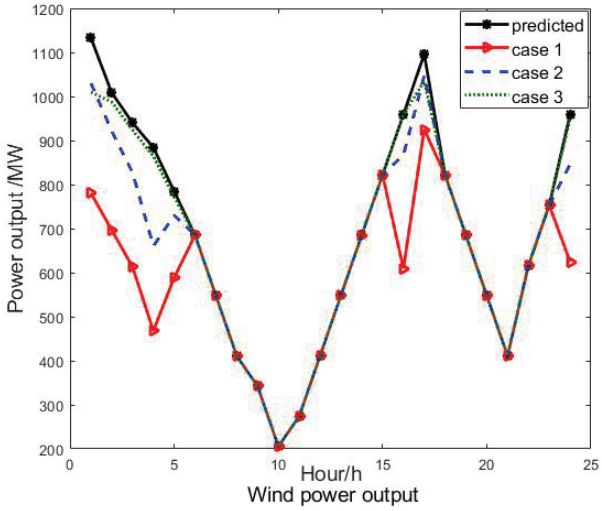

Fig. 3 - Predicted wind power output and actual wind power output in three case studies.

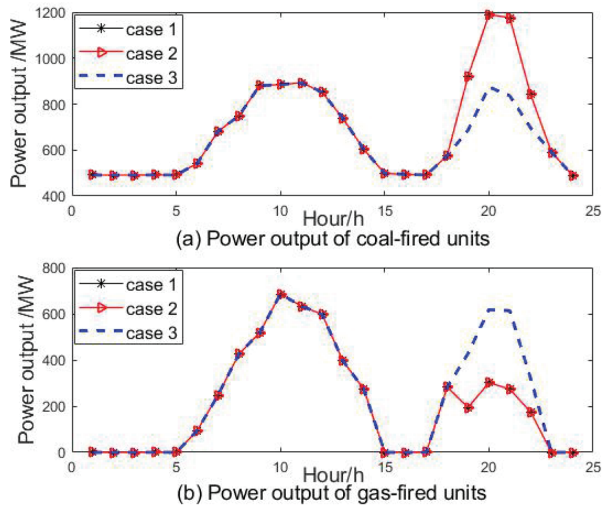

Fig. 4 - The power output of coal-fired generator units and gas-fired generator units.

From the results comparison between P2H (with maximum hydrogen mixture level 3% vol) and P2M, the following differences are apparent.

(1) Compared with operational cost of case 3, the operation cost of case 2 is declined by $10000 due to the higher efficiency of P2H. Moreover, the CO_2 emissions of case 2 are reduced by 170 tonnes as the hydrogen-natural gas mixture has lower CO_2 emissions per unit cubic meter. It can be seen that the economic and environmental impact of P2H is more prominent.

(2) Nevertheless, from Table 1, Table 4 and Fig. 5, it is quite obvious that the P2M absorbs much more wind power and has much lower wind power curtailment as the natural gas network has no limits for methane to be injected into. It is precisely because of it, some gas node pressure could be over the pressure limits when a lot of

methane is injected. Then the proposed management strategy is used as shown in Fig. 2 and the gas-fired generator units contribute much more power generation when P2M is considered as shown in Fig. 4.

(3) From Table 3 and Fig. 6, it can be found that the volume of gas in storage is much larger with P2H than that with P2M because when P2M is operated, a lot of natural gas is consumed by gas-fired generator units to manage the node pressure and then the gas from storage is used more than the gas from gas wells in later time periods due to its lower cost.

From the above analysis, it can be concluded that both P2H or P2M can benefit the hybrid power- natural gas energy systems in terms of cost and emissions reduction and improved wind power accommodation.

Hours	Case 1		Case 2		Case 3	
	Gas well 1	Gas well 2	Gas well 1	Gas well 2	Gas well 1	Gas well 2
1	0.6607	0.4464	0.8289	0.4482	0.8349	0.4318
2	0.6023	0.3715	0.4874	0.3730	0.4088	0.3646
3	0.4406	0.3585	0.5896	0.2304	0.3278	0.3609
4	0.5715	0.3699	0.2926	0.3114	0.5901	0.3653
5	0.4336	0.4457	0.2578	0.2598	0.4925	0.3663
6	0.5761	0.3552	0.4174	0.3122	0.5752	0.3467
7	0.6427	0.3444	0.8188	0.4729	0.6331	0.3756
8	0.7408	0.4027	0.5291	0.4146	0.6143	0.3655
9	0.5004	0.3921	1.1757	0.3856	0.6975	0.3829
10	0.5782	0.3674	0.3656	0.3526	0.6514	0.4517
11	0.5130	0.3675	0.4838	0.4086	0.9102	0.3413
12	0.5738	0.4528	1.0065	0.4475	0.6898	0.3598
13	0.8468	0.3669	0.7166	0.4009	0.5926	0.4209
14	0.4764	0.5356	0.5913	0.4084	0.5278	0.3659
15	0.4719	0.3654	0.5535	0.4263	0.5775	0.3925
16	0.5899	0.3788	0.6969	0.3577	0.6628	0.3632
17	0.6414	0.3655	0.3179	0.4693	0.5383	0.3658
18	0.6824	0.3919	0.8392	0.4344	0.4651	0.4183
19	0.7185	0.3779	0.5652	0.4700	0.9992	0.3289
20	0.8472	0.4535	0.9900	0.3754	0.6496	0.5140
21	0.6178	0.3720	0.7239	0.4707	0.6482	0.4524
22	0.8824	0.3421	0.4444	0.4363	0.5858	0.5398
23	0.5802	0.3610	0.6046	0.3614	0.4966	0.3412
24	0.6157	0.3745	0.4704	0.3831	0.5439	0.4017

Table 2 - Gas flow of gas wells in three case studies (Mm^3/h).

Hours	Case 1			Case 2			Case 3		
	Storage 1	Storage 2	Storage 3	Storage 1	Storage 2	Storage 3	Storage 1	Storage 2	Storage 3
1	0.0114	-0.0537	-0.1796	0.0535	-0.0181	-0.1024	0.1070	-0.1183	-0.1310
2	0.0030	-0.0777	-0.0430	-0.0836	-0.0663	-0.0325	-0.0530	0.0276	-0.1537
3	-0.0164	-0.0050	-0.2063	-0.0989	0.0283	-0.2020	-0.2000	-0.0674	-0.0692
4	-0.0715	-0.0071	-0.0178	-0.0343	-0.0196	-0.2500	-0.0090	-0.0230	-0.0498
5	-0.2000	-0.0004	-0.0221	-0.2000	-0.0295	-0.2471	0.0284	-0.0600	-0.1171
6	-0.0302	-0.0375	-0.0729	-0.1023	-0.0452	-0.1919	0.0301	-0.0415	-0.2133
7	0.0775	-0.1733	-0.1519	0.1853	-0.1807	0.0007	-0.1232	-0.0534	-0.0149
8	0.0369	-0.0922	-0.0994	-0.1234	-0.1069	-0.0912	-0.0026	-0.1890	-0.1623
9	-0.1015	-0.2280	-0.1518	0.3500	-0.1637	-0.0175	0.0130	-0.1882	-0.1251
10	-0.0077	-0.1641	-0.2500	-0.1965	-0.1235	-0.2385	0.1087	-0.2500	-0.1685
11	-0.1414	-0.2252	-0.2203	-0.2000	-0.2500	-0.1278	0.0087	-0.0774	-0.1192
12	-0.0711	-0.2120	-0.0850	0.1091	-0.1225	0.0000	0.0514	-0.1550	-0.1538
13	0.0535	-0.0398	0.0000	0.0106	-0.0588	0.0029	-0.0572	-0.1928	-0.0223
14	-0.0167	-0.2394	0.0000	0.0089	-0.2500	-0.0028	-0.0935	-0.2404	0.0002
15	-0.0624	-0.0812	0.0000	0.0098	-0.0206	0.0015	0.0160	-0.0191	-0.0002
16	0.0591	-0.1411	0.0029	0.0663	-0.0220	-0.0016	-0.0020	0.00364	0.0010
17	0.0058	-0.0151	-0.0012	-0.0781	-0.1695	0.0092	-0.0296	-0.1327	0.0004
18	-0.0074	-0.1900	0.0005	0.1170	-0.0150	0.0000	-0.0983	-0.2229	-0.0014
19	-0.0700	-0.0172	0.0013	0.0160	-0.2427	-0.0092	0.2147	-0.0833	-0.2097
20	-0.0649	0.0000	-0.0036	0.0901	0.0082	0.0000	0.0254	-0.1390	-0.0532
21	-0.1810	0.0000	0.0000	0.00375	-0.1315	0.0000	-0.0703	-0.2500	-0.0324
22	-0.0038	0.0000	0.0000	-0.1999	-0.0005	0.0000	0.0022	-0.0632	0.0000
23	-0.0253	0.0000	0.0028	-0.0248	0.0002	-0.0001	0.0145	-0.1972	0.0000
24	-0.0119	0.0000	-0.0029	-0.1536	-0.0003	0.0000	-0.0428	-0.0261	0.0000

Table 3 - Gas flow of gas storage in three case studies (Mm^3/h).

Hours	Case 1		Case 2		Case 3	
	P2H/P2M 1	P2H/P2M 2	P2H 1	P2H 2	P2M 1	P2M 2
1	0	0	0.0366	0.0149	0.0126	0.0008
2	0	0	0.0231	0.0232	0.0101	0.0068
3	0	0	0.0296	0.0146	0.0128	0.0054
4	0	0	0.0367	0.0029	0.0223	0.0008
5	0	0	0.0262	0.0030	0.0083	0.0024
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0.0531	0	0.0204	0
17	0	0	0.0251	0	0.0064	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	0	0	0	0.0001	0	0
23	0	0	0	0	0	0
24	0	0	0.0251	0.0205	0.0128	0.0065

Table 4 - Gas flow of P2H/P2M in three case studies (Mm^3/h).

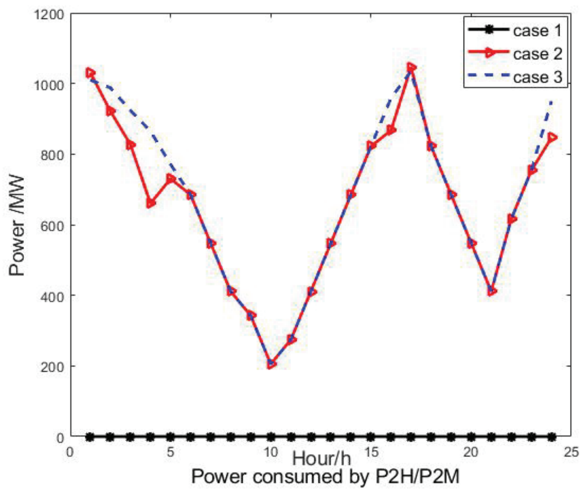

Fig. 5 - The power consumed by P2H/P2M.

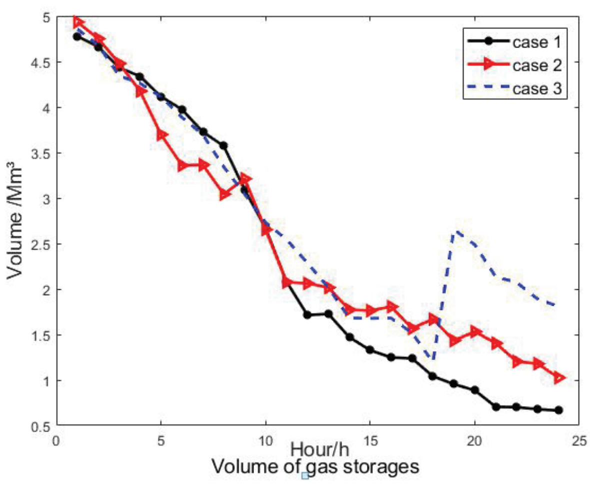

Fig. 6 - Volume of gas storages.

4 Conclusions

This paper presented an optimal operation model of hybrid power-natural gas energy systems considering P2H and P2M to achieve the minimum operational cost as well as the maximum wind power accommodation. The proposed model not only handles bi-directional energy flow between power systems and natural gas systems, but also considers the limits of hydrogen mixture level, line pack of pipelines and other complex system characteristics. A method for calculating higher heating value of the gas mixture as well as the hydrogen mixture level limits constraint handling method is proposed. Three case studies are carried out and the simulation results illustrate that both P2H and P2M can significantly benefit the hybrid power-natural gas energy systems in reducing operational cost, declining CO_2 emissions and avoiding wind power curtailment. Specifically, the operational cost is reduced by $15000 (with P2H) and $5000 (with P2M), respectively. And the total CO_2 emissions are reduced by 920 tonnes (with P2H) and 750 ton (with P2M), respectively. The excess wind power drops to 5.05% (with P2H) and to 1.60% (with P2M), respectively. Moreover, the differences between P2H and P2M in operational cost, CO_2 emissions, wind power accommodation, power output of gas-fired generator units as well as the operation of gas storage are compared and analyzed.

The operation model and algorithm used in this paper can be extended to solve the operation optimization problems of other hybrid energy systems. Besides, the work in this paper provides a way for the acquisition and use of hydrogen energy. In the future work, we will take heat energy system and seasonal storage into consideration. The environmental benefits could also include the impacts on human health and ecosystem quality.

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